of the wires are connected to a microcontroller or data acquisition device where the voltage difference between the two wires is measured. This voltage difference can be mapped to a temperature based on the type of thermocouple used. Other thermal measurement techniques could be used and communicate the temperature based on individual operating principles. The temperature measurements serve as inputs to the controller where they can be converted into electrical signals representing temperature and compared to the stored look-up table or equations. The look-up table or equations can contain normal and abnormal temperature distributions for a variety of boundary and operating conditions, and the temperature measurements can quickly be matched to a stored temperature distribution.

[0037] If the sensed temperature distribution is not representative of a healthy operating condition, the microcontroller can relay that information to any number of individuals including, but not limited to, the user, the manufacturer, and/or emergency personnel. The microcontroller can then interact with other parts of the BMS, including the thermal management system, and take corrective action. For example, if the values differ by a certain amount or percentage or if this percentage changes in a certain manner with time, then it could signify an anomaly, with some decision support, a reliability or safety problem, and/or halt further battery operation. In some embodiments, the trigger for reporting an anomaly can be established using a machine learning algorithm, statistics, rules derived from experiments, or data analytics.

[0038] In another implementation, the temperature distribution can be used to assess the health or performance of the entire battery pack, as well as individual cells for maintenance actions. At elevated temperatures, the battery can degrade at an accelerated rate. This information could be relayed to the user, the manufacturer, the dealer, or any other individual. The information can also be stored in memory for warranty, maintenance, or resale purposes.

[0039] The operating conditions can be used to identify the appropriate look-up table or equation that should be used to assess the state of the battery. Using sensor inputs to measure the operating temperature, the pack voltage, pack current, and any other relevant boundary conditions, the most applicable look-up table or equation can be accessed from storage. Using pattern recognition and health management algorithms, such as neural networks or support vector machines, one can then assess the health and/or safety of the battery system, including all the cells of the battery pack.

[0040] In the simplest approach this assessment might be just a comparison of an estimated temperature given specific operating conditions against a measured value of temperature, such as the outside temperature as a reference temperature. Health and/or safety assessment of the pack or individual cells could be incorporated into the algorithms ahead of time by adjusting the computer-aided design models to account for degradation of the battery system, battery pack, or battery cell and changes in the temperature distribution as the batteries age. These changes can be further verified with experimental tests using different combinations of aged and healthy cells to create a large database of look-up tables or equations. As the temperature distributions change over time under known operating conditions, the health and/or safety of the cell or pack can be assessed in conjunction with other health-related battery information such as discharge capacity and internal resistance. A graphical user interface can be incorporated into a system that informs users of the effect of their usage patterns on the battery's degradation. Users can decide whether to alter their behavior to prolong battery life.

[0041] FIG. **5** represents experimental temperature data collected from three different samples of the same lithium-ion battery pouch cell. At different usage conditions (discharge rate given as a multiple of the battery's capacity, C), the battery undergoes time variant temperature changes. These changes in the cell's thermal behavior can affect the thermal profile in the battery pack and are captured in the offline modeling to build the look-up table or equation.

[0042] FIG. **6** demonstrates that the modeled results for a cell accurately match experimentally obtained cell temperatures during discharge and charge at a variety of rates. Computational modeling of a battery pack can be used to predict the thermal profile variations when the cell is in use by defining the appropriate boundary conditions and use profiles.

[0043] The methods of the invention can be extended to optimal control of battery charging procedures. In many applications, rapid charging may be desirable. Knowledge of predetermined temperature distributions could be used to accelerate charging while maintaining the battery in a safe temperature range. Deviations from predicted temperature distributions can be used to alter the charging profile or enable active thermal management strategies to continue charging at a high rate.

[0044] Additionally, the methods described herein can be extended in fleet applications by identifying similar aging trends across the fleet and using the information to perform over-the-air (OTA) BMS updates to the temperature look-up tables and equations. Outlier systems can be identified and investigated (through physical maintenance or life cycle history analysis) to determine the source of error

[0045] Finally, the methods described herein can be used to guide condition-based maintenance strategies, notify first responders of potential safety issues, or implement safety measures. For example, the localization of a fault can be used to direct thermal management to the fault location or to cause the BMS to discharge surrounding batteries to lower the impact of cascading failures.

[0046] The approach could be extended to diagnostics and localization of unhealthy or faulty cells. If the temperature distribution does not match any of the modeled temperature distributions, a built-in test function could be enabled to test the internal resistance or voltage of each cell, or a subset of cells, individually. This approach could assist in determining if the anomaly is safety-critical (excessive temperature due to a short circuit) or simply a performance issue (higher internal resistance leading to joule heating). Additionally, it could be used to localize heat zones that are receiving insufficient cooling. If there is an obstruction in the cooling line between groups of cells, the inefficient cooling could be detected through the abnormal temperature distribution.

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